Outlook/Discussion for "Prospects of the String Axiverse 2025"

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Outline

- Field-theoretic vs. stringy axions
- Model dependence of string axions
- Interplay with inflation / dark radiation
- A related subject: Stringy hidden photons etc. ...
- Statistics / geometrical constraints
  (related to this: the dS elephant in the room)
- Is a 'broader (swampland) perspective' possible and useful?

Preliminary comments

- My focus, through not exclusively, will be on the QCD axion (taking a fundamental-theory-driven perspective).

QCD axion:

$$\mathcal{L} \;\supset\; \theta F_{QCD}\tilde{F}_{QCD} \;+\; \frac{1}{2}f^2(\partial\theta)^2 \;+\; \Lambda^4_{QCD}\cos(\theta)\,.$$

(QCD-induced potential dominates θ-dynamics, driving it to zero.)

- I will be strongly influenced by the review-part of our paper 'Axions in string theory – slaying the Hydra of dark radiation' with Cicoli/Jaeckel/Wittner.

Axion origins:

(1) Field-theoretic: $\varphi = \langle\varphi\rangle e^{i\theta}$

Needs model building; in general faces 'quality problem'.

see e.g. Kamionkowski/March-Russell '92 ...

... recent attempt: Babu/Dutta/Mohapatra '24

(2) Fundamental (stringy or *p*-form) axion: $\theta \sim \int C_p/B_2$

Axion arises as *p*-form gauge field in 10d, integrated over cycle of Calabi-Yau. $\Rightarrow$ Perturbatively flat potential by gauge symmetry.
$\Rightarrow$ Excellent quality for free.

Finally, the SUSY structure $\mathcal{L} \supset TW_\alpha W^\alpha|_{F-term}$; $T = \tau + i\theta$

automatically leads to the desired coupling $\mathcal{L} \supset \theta F\tilde{F}$.

see e.g. Conlon, Svrcek/Witten '06

Questions:

- Are we devoting enough attention to ‘Field Theory Axions’ in string theory?

  Some refs. have been collected in our ‘Axions in ST – Slaying the Hydra...’ and in M. Reece’s ‘Extra-dimensional axion expectations’.

- What is a good nomenclature?

  (‘field-theory axions’, ‘model-building axions’, ‘open-string axions’, ‘secondary axions’
  vs.
  ‘*p*-form axions’, ‘stringy axions’, ‘closed-string axions’, ‘extra-dimensional axions’)

- If ‘Option **(1)**’ can always be viewed as ‘fine-tuned’ our ‘contrived’, can we possible even claim that

  The Discovery of a (QCD or other) axion is **evidence for string theory in the 10d-SUGRA regime?**

Personal conclusion so far:

Option **(2)** of a *p*-form axion is much preferred.

Known problem / challenge in this context:

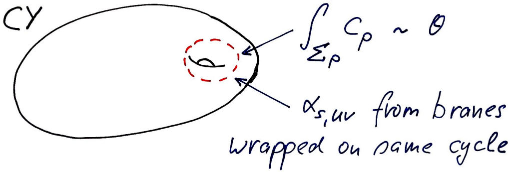
Conlon, Svrcek/Witten '06

Non-trivial to realize the preferred value $f \ll M_P$.

Leading approach: Large compactification volume.

(based simply on $M_P^2 \sim \mathcal{V}$, $\alpha_s(M_P) \sim 1/Vol(\text{SM-cycle}) \sim 1$

and hence $f \sim M_s$.



$$\Rightarrow \qquad \frac{f^2}{M_P^2} \sim \frac{1}{\mathcal{V}}$$

More explicitly:

- For type-IIB with C_4-axion:

$$\frac{f_{min}^2}{M_P^2} \sim \frac{\alpha_{s,\,UV}}{\sqrt{g_s}\,\mathcal{V}}$$

- For LVS:

$$\frac{f_{min}^2}{M_P^2} \sim \frac{3\gamma_L}{16\pi^2\sqrt{\tau_L}\,\mathcal{V}}$$

Questions:

- How badly do we want $f \ll M_P$?
- How unique is the solution $f/M_P \sim 1/\sqrt{\mathcal{V}} \ll 1$?

Note:

Warping may represent an alternative path towards small f.
But it is technically not easy to realize....

Svrcek/Witten '06, Dasgupte/Firouzjahi/Gwyn '08
Buchbinder/Constantin/Lukas '14, Im/Nilles/Olechowski '19, ...

Realizing a large volume:

- KKLT: Naively appears hopeless since 4-cycle volumes are only logarithmically large: $\tau \sim \ln(1/W_0)$.

  But large number of terms in $\mathcal{V} \sim \kappa_{ijk} t^i t^j t^k$ may help to a certain extent....

  various studies by Cornell group...., talk by Jakob

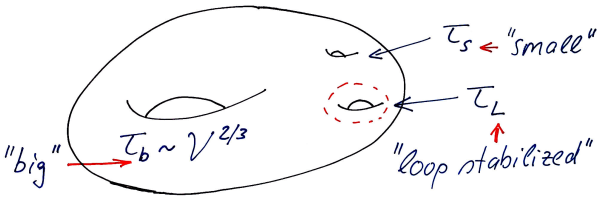
  (Demirtas, Gendler, Long, McAllister, Moritz, Marsh, ...)

- LVS: exponentially large volume built in! $\mathcal{V} \sim \exp(\mathcal{O}(1)/g_s)$

- perturbative stabilization.... ???

Large Volume Scenario (LVS) with loop-stabilized cycle

- The best-controlled way of getting the required large volume $\mathcal{V}$ above appears to be the 'LVS'.
- It is based on CYs with a big and a small 4-cycle. (In our case with a further cycle 'τ_L' stabilized by loop effects.)



- Supergravity description:

$$K = -2\ln(\mathcal{V} + \xi/g_s^{3/2}) \; ; \qquad \mathcal{V} = \tau_b - \gamma_s \tau_s^{3/2} - \gamma_L \tau_L^{3/2} \; ;$$

$$W = W_0 + e^{-\tau_s} \qquad \Rightarrow \qquad \boxed{\mathcal{V} \sim e^{\tau_s} \sim e^{1/g_s}} \, .$$

Questions

- It appears that, beyond the initial very positive claim about the genericity of stringy axions, we immediately get 'entangled in the model-dependent details'?
- Is this unavoidable?
- Is this a curse or a maybe a positive feature of string pheno? (In the sense that we actually learn about higher-dimensional origin of the SM?)

.... let's add some more details
(following again Cicoli/AH/Jaeckel/Wittner '22)

Key cosmological bounds

DM: $\Omega_{DM} \gtrsim 0.2 \left(\frac{f}{10^{12}\text{GeV}}\right)^{7/6} \theta_i^2$ (with 'i' for initial)

Isocurvature perturbations: $H_I \lesssim 1.4 \cdot 10^{-5} \; f \, \theta_i$

Using also $f \sim \frac{1}{\sqrt{\mathcal{V}}}$ and $\theta_i \lesssim \left(\frac{10^{12}\text{GeV}}{f}\right)^{7/12}$, one finds

$$\Rightarrow \quad \boxed{H_I \lesssim \frac{10^9\text{GeV}}{\mathcal{V}^{5/24}}}$$

Combining $H_I \lesssim (10^9 \mathrm{GeV}/\mathcal{V}^{5/24})$

with the general expectation $H_I^2 \sim V_{LVS}/M_P^2 \sim (W_0^2/\mathcal{V}^3) M_P^2$,

one finally has:

$$\Rightarrow \boxed{\mathcal{V} \gtrsim 10^7} \quad ,$$

i.e. we are deeply in the 'LVS regime'.

Aside on Dark Radiation:

- In the deep-LVS regime, one faces a dark radiation problem due to the big-cycle axion.

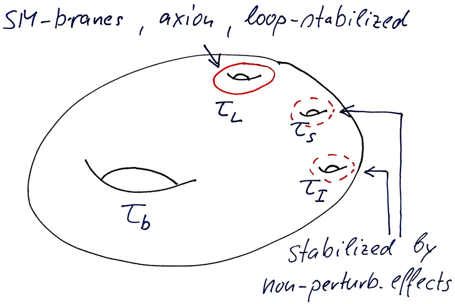
Cicoli/Conlon/Quevedo, Higaki/Takashi '12
AH/Mangat/Rompineve/Witkowski '14

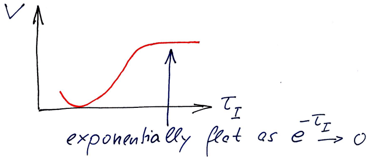
- The reason is that, at least naively, the big-cycle modulus dominantly decays to its own axion.
- However, this changes if the SUSY-breaking scale is high (as is always the case if one wants a QCD axion).
- The reason is that the Higgs mass is small by fine-tuning and it is the natural Higgs mass scale which governs the modulus decay to the SM.
- Thus, the decay to the SM wins over the axion-decay.

→ 'Slaying the Hydra of Dark Radiation...'

Aside on Inflation:

- Accepting that we need a very large volume, we unavoidably get a very low inflation scale.
- This requires a very flat potential, and the only established candidate appears to be blowup inflaton. Conlon/Quevedo '05'





- But loop corrections unavoidably spoil blowup inflation, turning it into loop blowup inflation, with **very** different pheno characteristics. Bansal/Brunelli/Cicoli/AH/Kuspert '24

Questions:

- Is the very-low-scale inflation apparently required for a realistic QCD axion a serious/generic problem?

- Can ‘fluxbrane inflation’ (using D7-brane moduli) provide the right parameters?

  several papers with Lüst/Weigand et al. in ’11...’14

- Is the recently discussed ‘back-to-the-origins’ version of D3-anti-D3 inflation another alternative?

  Cicoli/Hughes/Kamal/Marino/Quevedo

More generally:

- How trustworthy / useful in the present context are entirely perturbative stabilization schemes? $(\delta K \sim \ln(\tau)/\tau^{3/2})$

  Weissenbacher .... Klaewer et al. .... Antoniadis/Chen/Kounnas .... Cicoli et al.

How model dependent is the stringy QCD axion?

- According to recent conceptual and statistical work (in type IIB with O3/O7, $h^{1,1} \gg 1$), the axion solution to the strong CP problem can be easily spoiled.

  (High-scale QCQ instantons $+$ instantons from other cycle)

Broeckel/Cicoli/Maharana/Singh/Sinha
Demirtas/Gendler/Long/McAllister/Moritz

Questions:

- Should we be concerned, or are we OK that an $\mathcal{O}(1)$ fraction of models works?

- How meaningful are such analyses without a quantitative understanding of the required 'perturbative Kahler moduli stabilization'? (not necessarily of $\mathcal{V}$ but at least of τ_{SM}).

Broader 'model dependence issues'

- 'Heterotic axions' are hard to get – for well-known reasons. (Still, what's the status of string pheno here?)
- Are there special axion features in F-theory?
- Are we really OK with completely dismissing type IIA (Because we don't know how to uplift DGKT?)

Beyond the QCD axion

(.. recalling the much broader original scope of the 'string axiverse')

Arvanitaki/Dimopoulos/Dubovsky/Kaloper/March-Russell '09

- How certain are we – with today's deeper understanding – that 'axions are abundant'? Which axions? Which concrete settings? (Moduli stabilization!)

Concretely: 'fuzzy axions'

(Significant part of DM; light enough for astrophysical impact...)

[1] Cicoli/Guidetti/Righi/Westphal
[2] Sheridan/Carta/Gendler/Jain/Marsh/McAllister/Righi/Rogers/Schachner

- 'How fuzzy' does an axion need to be for us to notice? (How will the bounds improve?)
- What about the fundamental tension between fuzziness and DM-abundance uncovered in [1]?

Beyond axions

- Apart from the QCD axion (for which we arguably have experimental evidence), string axions are just one of the many 'light hidden sector particles' which generically appear in string models
- So it's justified to look more broadly, including e.g.

Dark Photons

- Could we claim them to be as natural a prediction of string theory as axions?
- Observability is, of course, different (but not necessarily worse), $\rightarrow$ kinetic mixing.

Aside on kinetic mixing

- Apparently a very old and well-studied subject.

  Dienes/Kolda/March-Russell '96, Abel/Schofield '03, Goodsell/Jaeckel/...
  .../Khoze/Redondo/Ringwald '08, Bullimore/Conlon/Witkowski '10, ...

- More recently revived in swampland context.

  Benakli/Branchina/Laforgue-Marmet '20, Obied/Parikh '21

- Still, even some of the most basic questions remain unanswered (parametric size of kinetic mixing between two sequestered D3-sectors).

  AH/Jaeckel/Kuespert '23

  Specifically: 4d SUSY forbids (by holomorphicity and shift symmetry) the Kahler moduli dependence that explicit 10d SUGRA calculations appear to predict.

The elephant in the room: Problems with de Sitter

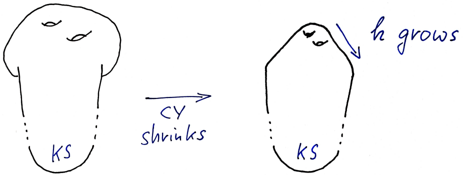
- We know that SUSY-breaking/uplifting can affect the phenomenology of a given compactification strongly.
- Even worse: Some otherwise attractive compactifications may have no uplift.
- During the last decades, this has put heterotic/IIA models somewhat in the background compared to IIB/F-theory.
- Indeed, the KKLT/LVS proposals have historically made (many of) us believe that IIB models can generically be uplifted.
- Due to recent developments, there is reason to doubt this!

... a lightning review:

KKLT

- Parametricall, the throat is larger than the CY.

Carta/Moritz/Westphal '19



- This implies excessive warping and a 'Singular bulk problem'

Gao/AH/Junghans '20

- Control is lost (at least in the standard 'KKLT way')

see however Carta/Moritz '21, McAllister/Moritz/Nelly/Schachner '24

LVS

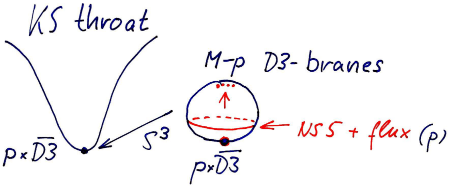
- Similar control issues potentially arise in the LVS, not due to warping but to α' corrections in the bulk

  Junghans '22, Gao/AH/Schreyer/Venken '22, Junghans '22

- While control can be maintained for large-enough negative D3-tadpole, known geometries (marginally) do not meet the demand.

  Gao/AH/Schreyer/Venken '22

- This becomes **much** worse if one quantifies the control against (KPV) brane-flux transitions including NS5 α' corr.s (the required throat becomes much bigger, and hence the required tadpole)



Why are these 'dS issues' relevant here?

- Even admitting optimistically that some form of KKLT/LVS can be saved, we don't know which one and at which (statistical) cost.

- Thus, all expectations of 'natural' axions may be overthrown.

- For example, let's say an (obviously highly tuned) F-term uplift using CS-moduli can be realized.

  Saltman/Silverstein, Denef/Douglas, Gallego/../Wrase, AH/Leonhardt, Krippendorf/Schachner, Lanza/Westphal

- If, as expected, this is very hard, we may find a strong bias towards large $h^{2,1}$ and hence small $h^{1,1}$. Then we will generically not see the many C_4 axions we usually count on.

- Clearly, many analogous 'strong bias' stories can be invented....

Summary/Conclusions

Plus:

- Can we make a precise, scientific claim that an axion discovery is evidence for string theory?
- Can we decide which part of the landscape this puts us in?

Minus:

- Is any of the above even meaningful before the 'dS issue' is settled?
- Similarly, doesn't the purely understood landscape statistics / measure problem make the above impossible?

Many questions – few answers – lots to do !

Backup Slides

The coupling to the Higgs originates in the Kahler potential

$$K \supset -3\ln\left(T_b + \overline{T}_b + \frac{1}{3}(H_u\overline{H}_u + H_d\overline{H}_d + zH_uH_d + \text{h.c.})\right)$$

$$\Rightarrow \qquad \mathcal{L} \supset zH_uH_d\,\partial^2(\ln\tau_b)\,.$$

This is comparable to the standard, Kahler-potential-based coupling of τ_b to its own axion θ_b, such that:

$$\Rightarrow \qquad \Gamma_{\tau_b \to \mathrm{SM\ or\ }\theta_b\theta_b} \sim \frac{m_{\tau_b}^3}{M_P^2} \qquad \Rightarrow \qquad \Delta N_{eff} \gtrsim \mathcal{O}(1)\,.$$

(Recall: observationally, $\Delta N_{eff} \lesssim 0.2\cdots0.4$.)

Crucial new point: This will change for high-scale ~~SUSY~~.

Volume modulus decay for high-scale ~~SUSY~~

- Dominant effect now due to mass term: $\mathcal{L} \supset -m_h^2(\mathcal{V})\, h^2$.

$$m_h^2(\mathcal{V}) \;\sim\; m_{3/2}^2 \left[c_0 + c_{loop} \ln\left(\frac{m_{KK}}{m_{3/2}} \right) \right]$$

- This is the famously fine-tuned small eigenvalue of the MSSM Higgs mass matrix.

- The running of its loop correction is governed by:

$$m_{KK} \equiv m_{KK,\tau_s} \sim M_P/\sqrt{\mathcal{V}} \quad ; \qquad m_{3/2} \sim M_P \cdot W_0/\mathcal{V} .$$

- Using $\mathcal{V} \sim \tau_b^{3/2}$ this gives

$$\boxed{\mathcal{L} \;\supset\; m_{3/2}^2\, c_{loop}\, h^2\, \delta(\ln \tau_b) .}$$

Volume modulus decay for high-scale ~~SUSY~~ (continued)

- The resulting rate is governed by the pre-fine-tuning scale $m_{3/2}^2$ of the Higgs mass term:

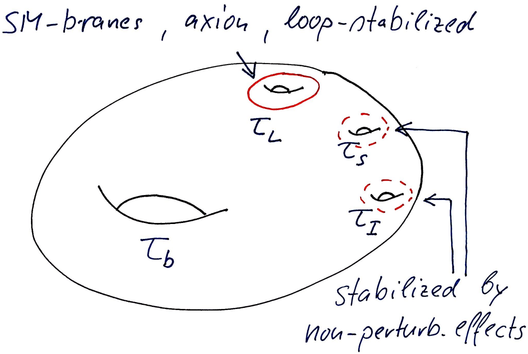
$$\Gamma_{\tau_b \to hh} \sim \frac{m_{3/2}^4 c_{loop}^2}{m_{\tau_b} M_P^2} \sim (c_{loop}\mathcal{V})^2 \frac{m_{\tau_b}^3}{M_P^2} \gg \Gamma_{\tau_b \to \theta_b\theta_b} \,.$$

(Head one of the Hydra is gone.)

- Does this solve the DR problem? Not necessarily since
  - τ_b now decays too fast.
  - It loses its role of the particle reheating the universe.
  - Instead, one expects this task to fall to the inflaton, potentially re-introducing a DR issue.

(This is head two, to be dealt with montarily....)

String inflation in the LVS and reheating



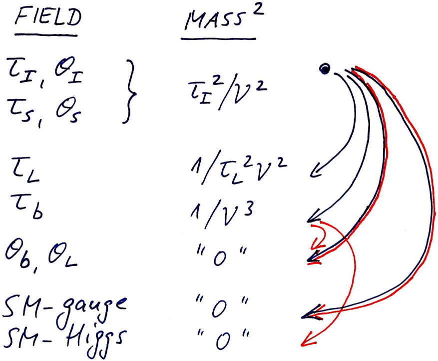
- The hierarchy of cycles is $\tau_b \gg \tau_L \gg \tau_s, \tau_I$
- for the loop-stabilization of τ_L we use the ansatz

Cicoli/Goodsell/Ringwald

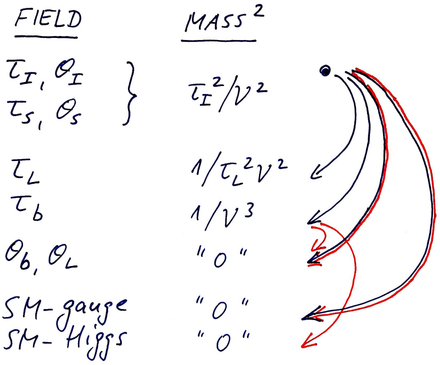
$$V_{loop} = \left(\frac{\mu_1}{\sqrt{\tau_L}} - \frac{\mu_2}{\sqrt{\tau_L} - \mu_3} \right) \frac{W_0^2 M_P^4}{\mathcal{V}^3}$$

- The detailed analysis of decay rates in this setting shows that kinetic-term-induced decays dominate.
  (cf. our 20-page Appendix following Cicoli/Mazumdar '10)

- Mass hierarchy:



- Key point made before: The decay of τ_b to the SM Higgs is fast and dominates over the decay to its axion.



- The decay rates of τ_I shown above are all parametrically of the order of $\Gamma_1 \sim \frac{(\ln \mathcal{V})^{9/2}}{\mathcal{V}^4} M_P$.

- The crucial numerical ratios are specified by

$$\frac{\Gamma_{\tau_I \to \tau_b \tau_b \,/\, \theta_b \theta_b}}{\Gamma_1} = 1 \,, \qquad \frac{\Gamma_{\tau_I \to \tau_L \tau_L \,/\, \theta_L \theta_L}}{\Gamma_1} = 4 \,, \qquad \frac{\Gamma_{\tau_I \to \text{SM gauge}}}{\Gamma_1} = 8 N_g \,.$$

- The crucial large rate to gauge bosons arises because τ_l mixes with τ_L, and the latter directly governs the SM gauge coupling.

- Eventually, DR branching ratio and abundance are:

$$BR(\tau_l \to \mathrm{DR}) \simeq \frac{5}{8N_g} = \frac{5}{8 \cdot 12} \simeq 0.05\,.$$

$$\Delta N_{\rm eff} \simeq 6.1 \left(\frac{11}{g_*}\right)^{1/3} BR(\tau_l \to \mathrm{DR}) \simeq 2.8\, BR \simeq 0.14\,.$$

- This is a rather specific prediction and an interesting target for future CMB observations.

- The relative smallness originates in $N_g = 12 \gg 1$.

Sweet-spot cosmology (high-temperature regime)

- The lowest allowed volume (without excessive tuning) is

$$\mathcal{V} \sim 10^7 .$$

- This implies

$$f \sim 10^{14}\,\text{GeV}\,, \qquad m_{3/2} \sim 10^{11}\,\text{GeV}\,, \qquad m_{\tau_b} \sim 10^7\,\text{GeV}.$$

- Resulting inflation scale and reheating temperature (based on the decay rates above):

$$H_I \sim 10^7\,\text{GeV}\,, \qquad T_R \sim 10^6\,\text{GeV}.$$

- In summary, this is a fairly standard cosmology, with some tension concerning the (potentially low) CMB-normalization.
  $\Rightarrow$ More work on blowup-inflation pheno needed.